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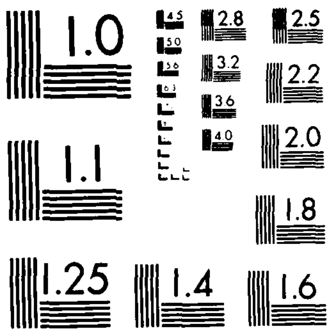

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BIOPHYSICAL EVALUATION OF FOOTWEAR FOR COLD-WEATHER CLIMATES

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Running head: Footwear for cold-wet climates

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Proper selection of footwear for cold-wet environments is important in determining individual performance and comfort. Results based on testing only total dry insulation (I_t) are not an adequate basis for boot selection. In this study, regional insulation values were obtained under dry conditions, then during a soak in shallow water and finally for insulation recovery after removal from water. Results for seven boots show no advantage for new synthetic materials during short soak episodes. Insulated leather-synthetic boots recover to dry insulation levels more rapidly than more traditional insulated leather boots. Rubber waterproof bottoms were the most effective boot construction for retaining insulation levels during water exposure. The study demonstrates an effective method for evaluating the effects of surface moisture on boot insulation. This method should lead to more knowledgeable selection of footwear for cold-wet climates.

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ABSTRACT

Proper selection of footwear for cold-wet environments is important in determining individual performance and comfort. Results based on testing only total dry insulation (I_t) are not an adequate basis for boot selection. In this study, regional insulation values were obtained under dry conditions, then during a soak in shallow water and finally for insulation recovery after removal from water. Results for seven boots show no advantage for new synthetic materials during short soak episodes. Insulated leather-synthetic boots recover to dry insulation levels more rapidly than more traditional insulated leather boots. Rubber waterproof bottoms were the most effective boot construction for retaining insulation levels during water exposure. The study demonstrates an effective method for evaluating the effects of surface moisture on boot insulation. This method should lead to more knowledgeable selection of footwear for cold-wet climates.

key words: insulation, cold injury, clothing

For individuals living or working in a cold climate the selection of adequate hand and footwear is a critical necessity. In response to long-term exposure to local environmental conditions, native populations have developed or adopted suitable technologies to protect the extremities (11). Modern industrial societies have tended to abruptly expose large populations of inexperienced, unacclimatized personnel to potential cold injury by uniformly equipping them with technically innovative, but frequently unrefined or inadequately field tested footwear designs. These populations, once engaged in massive construction projects or military campaigns, are frequently restricted by supply limitations, organizational dogma and task requirements to a very narrow range of potential responses in the event that the footwear fails to provide adequate protection. The pre-selection of adequate footwear for the given task and environment is an important factor in the prevention of cold injuries (7). Industrial societies depend on laboratory testing to evaluate and refine designs rather than the conservative evolution of functional designs followed by native populations. The adequacy of laboratory testing procedures is therefore a crucial factor in the successful development and evaluation of new footwear designs.

At present the insulation of footwear in our laboratory is tested by mounting specific prototype boots over a standard cushion foot sock on a regionally heated copper foot model in an environmental chamber. Boot

insulation is determined for each of 29 regions which correspond to thermal isolated sections on the model. Until very recently, only the weighted value for total insulation, I_t, was used as the criterion for comparing the insulation of different boots. The regional distribution of insulation however, may be a more important design feature of cold weather clothing than I_t. The dry insulation values for each individually heated section of the foot model and selected zones such as combined heel and toe serve as descriptors of efficiency of footwear in guarding against cold injury.

Current test methods examine footwear insulation only under dry conditions. But, the most difficult climate for cold weather footwear selection is the cold-wet condition where surface moisture often is absorbed into the insulating materials thereby significantly reducing protection from cold injury. The purpose of this paper is to show an approach for evaluating footwear which allows one to make a realistic evaluation of the functional insulation in footwear under wet conditions. On the basis of dry insulation values alone, a papier mache boot theoretically would appear to provide adequate cold weather protection. The criterion for determining if a particular boot provides adequate cold weather protection must be the amount of effective insulation under anticipated field conditions. The procedures described in this paper offer a positive step in developing the methods necessary to adequately evaluate prototype cold weather footwear.

METHODS

The basic test procedure employed was to mount a water resistant, vapor permeable (polytetrafluoroethylene (PTFE) base) sock over the sectionally heated copper foot (Figure 1) to waterproof the model.

Figure 1 here

A standard military cushion sock was placed over the PTFE sock. The boot was then tightly laced over the sock. A screw jack was used to apply a pressure of 70 kg against the bottom of the foot to simulate compression of insulation while walking. The insulation value of the boot was derived from measurement of the power demand required to maintain a constant temperature in each of 29 thermally isolated sections. This test procedure is essentially our standard method for evaluating footwear insulation and is an adequate method for comparing the dry insulating value of different boots. The boot was then placed in a plastic pan holding 5 cm of water and the test repeated. The boot was then removed from water and placed in the chamber under the same conditions as the initial dry run.

The test environment was an environmental chamber with automatic control. The box was set for a air temperature of $2^{o}C$, 50% relative humidity and an average air movement of 0.3 ms^{-1}. The surface of the copper model was controlled at $30^{o}C$.

The insulation values for each section were calculated every half hour by an internal program on a Hewlett-Packard 236 micro-computer control and data acquisition system. The basic formula utilized the area of each model segment (A_i, m^2), the power (P_i, W) and the temperature gradient (ΔT,K) between the model surface and the chamber ambient used to calculate the local resistance (R_i) to heat exchange according to the following equation:

$$R_i = A_i \Delta T / P_i$$

I_t was calculated as a weighted average, utilizing the A_i as the weighting factor.

Initially, boots were kept in the soak phase until the I_t insulation, plateaued. It became apparent that for several boots, the time required to reach a stable level of wet insulation was completely unrealistic in terms of time. After several tests, a uniform wet exposure of 7 hrs was selected. The recovery duration was variable but was at least a minimum of 7 hrs. After the initial tests, all tests were conducted with the pan of water in place but containing water only during the soak phase.

The boots tested include two low-cut uninsulated hiking boots. One of these two boots has a vapor permeable laminated lining. The leather-synthetic boot tested has a similar lining plus microfiber insulation. The leather combat and leather cold-weather boots were military prototypes finished with a silicon based leather treatment. The shoepac is a military prototype based on a commercial design. The mountain boot is a current military issue combination climbing-ski boot subjected to repeated testing. All other boots were in new condition.

RESULTS

Table I shows the results for short term exposure from tests of 7 different boots for total insulation, the boot sole, and the combined heel and toe regions.

Table I here

Figures 2 and 3 present the soak-recovery cycle for the leather cold-weather boot and the leather-synthetic boot, respectively.

Figures 2,3 here

The total length of the soak period was 31 hrs for the leather boot and 23 hr for the leather-synthetic boot. In the heel and toe region of the boots, Figure 2 shows a plateau, whereas Figure 3 displays an abrupt shift in the rate of insulation decrease near the end of the soak period. That shift may indicate a threshold to water resistance. Long-term recovery of insulation after removal of the boot from water is clearly slower for the leather boot. A comparison of the recovery of only the I_t values does not demonstrate the differences between the two boots as clearly as a comparison of the values for the heel or heel and toe regions.

The heavily insulated rubber-bottomed shoepac rapidly reached a stable low value for the same sections and I_t as shown for the cold weather leather boot and the synthetic-leather boot. Those data when plotted on the same scale as Figures 2 and 3 demonstrate virtually no vertical displacement and consequently the plot was not included in the analysis of this paper. The loss in insulation for the shoepac reflected only an increase in heat loss to a liquid substrate. A rapid recovery to original dry insulation values occurred because no moisture is absorbed into the boot. The contrast between the shoepac and

the boots in Figures 2 and 3 readily shows the advantage of waterproof boots over boots that absorb moisture when exposed to external moisture. These results reflect an advantage of footwear with completely waterproof bottoms that one would expect to experience in the field.

DISCUSSION

The problems associated with cold weather footwear are related to insulation, ventilation, bulk, foot support and traction (6). At the end of WWII, there were three general categories of cold weather boots available: porous, all leather boots, fully waterproofed boots and combination "shoepacs" with waterproof rubber bottoms and porous leather uppers. Supplemental insulation consisted of sheep shearling or wool felt. By 1944, the principles behind the "vapor barrier" boot which sandwiched a thick layer of insulation between two waterproof layers were being developed (8). That level of boot technology was fully developed during the Korean conflict and eventually became available to the civilian market.

Each of the three basic footwear types has advantages and short-comings. The porous all leather boot has adequate ventilation but absorbs surface water thereby decreasing insulation unless the leather is specially treated. Leather treatment to increase water resistance may reduce the ventilation by blocking natural pores and/or deteriorate as the boot is worn. The leather itself may

deteriorate with continued exposure and when removed from contact with moisture the recovery of the insulation value is relatively slow. The fully waterproof boot has poor ventilation, less flexible materials, and if wear causes a puncture in the waterproof layer(s) water may actually become trapped by the foot or in the insulation. The porous-waterproof combination shoepac combines advantages and disadvantages of the other two boot types. The shoepac is generally more durable than the all rubber boot, more flexible and has better ventilation. However, if water penetrates the porous leather uppers it may become trapped in the bottoms and the fit is not as good as leather boots. Except in extreme cold, soldiers are likely to encounter some surface water deeper than the boot tops but the frequency of such events is dependent on the locality.

The criticisms of each of the three basic boot types are based on footwear constructed from the materials available during WWII. New synthetic materials have become available for footwear manufacture since WWII. Synthetic uppers are not as susceptible to deterioration from repeated soaking. Water-resistant but vapor permeable fabrics may allow ventilation without absorbing water. Some synthetic insulating fibers may retain most of their insulating qualities when wet and micro-fibers may reduce the bulk of insulation. Other new insulation types include various plastic foams and synthetic pile. New plastics may produce a more durable and waterproof shell. The potential value of innovations in footwear materials for wet-cold

climates is not being effectively determined because standard test procedure can not wholly evaluate the effect of surface moisture on footwear insulation.

The selection of test exposure condition is important. Under cold-wet climatic conditions surface moisture exists in the form of precipitation, snow, streams or standing water. The level of exposure to environmental moisture depends on the individual's occupation. For example, military personnel routinely ford small streams, march through mud, standing puddles or snow then bivouac or occupy field fortification under wet conditions. If exposure of the outer footwear surface to surface moisture is of sufficient duration, maximum saturation of the boot materials will occur. Maximum environmental expose can be simulated by submerging the boot in water until total saturation of the footwear materials occurs. Such worst case tests fail to distinguish between boot materials with differing rates of water absorption. Although situations existed where individuals have worn footwear continuously for several days in standing water, a more realistic general field test is to expose footwear to shallow water for a shorter duration. Too short an exposure however will only discriminate between very porous materials and more resistant footwear.

The recovery of insulation after removal from contact with surface moisture is also important. In theory, the rate of absorption should be equal to the rate of recovery. The actual situation may be a breakdown of

resistance to water penetration through the outer layer which is not readily reversed because the moisture becomes trapped in the insulation or inside the boot (1). As the boot dries the resistance to water penetration may recover trapping moisture inside the boot. Furthermore, a small leak that was sufficient to admit water may be insufficient to allow complete drainage or enough ventilation to dry the inner boot, sock or insulation.

The results of this study showed that for new boots, silicone treated leather boots may perform as effectively as boots incorporating synthetic uppers if exposure to water is of relatively short duration. With wear, the leather treatment may deteriorate, resulting in a greater insulation loss. Wear may also compress or shift the position of insulation. It is anticipated that synthetic materials will not be as affected by normal wear. Long term storage, an important military consideration, can result in deterioration of both synthetic and leather products depending on both the storage conditions and the materials in the boots.

The hiking boot with the laminated waterproof, vapor permeable layer retained a higher percentage of the original dry insulation. The difference is essentially marginal for the two boots tested. It should be emphasized that the two hiking boots were dissimilar in terms of weight, leather thickness and general construction so direct comparisons are questionable. The use of a PTFE lining may prevent water penetration from the outside environment,

thereby protecting the insulating value of clothing layers inside the barrier; however, wet outside layers may reduce the effectiveness of vapor permeation by lowering the water vapor concentration gradient between the internal and external environment (4).

In previous footwear evaluation, boots that had I_t values that varied 10% or less were considered to offer equal protection from heat loss under conditions equivalent to the test conditions. Based on those criteria and the results in Table I for dry I_t, five of the seven boots should provide nearly equal protection. It might be assumed that boots which have "equivalent insulation" would provide equal protection from the cold. However, cold injury tends to affect the extremities of the foot first (2,5). In addition, the sensation of discomfort under cold conditions is associated primarily with the foot region (9,3). Hence both the wearer's perception of cold and susceptibility to cold injury is more dependent on local levels of insulation than the overall insulation (I_t) of the boot. Equivalent cold protection should mean that the insulation is equal for the critical regions in the two boots, not simply that their weighted I_t values are equal. A well designed boot with insulation concentrated in the regions of greatest heat loss potential can provide better protection than a boot with poorly distributed insulation but a higher I_t.

Of the five boots which would be equivalent on the basis of I_t alone, in terms of heat loss from the heel and toe regions under the initial dry conditions, the leather cold weather boot had the highest insulation value and only the leather-synthetic boot was within the 10% range of equality. When the insulation values at the end of a 7 hr soak period were compared, the leather boot exceeded the 10% margin over the other four boots. If, however, the recovery of insulation is determined to be an important criteria, the "best" boot may not be a leather boot. Under all of the conditions tested, the shoepac's insulation was the heaviest and best protected.

In an actual field situation, more is involved in the prevention of cold injury to the foot than just insulative properties of the boot. Different types of socks with moisture transmission ("wicking") properties or greater retention of insulation when wet or damp, sweat accumulation, proper foot care and opportunities to remove and dry both feet and footwear are also factors which determine the potential for cold injury (10).

In summary, the test procedures employed in this study sought to simulate the effects of moderate levels of external moisture which affect the insulation in footwear. The shoepac performed better than leather boots because the waterproof bottoms prevented insulation loss due to water penetrating the insulation. The insulation in water resistant leather boots was not reduced more than the insulation in boots constructed with synthetic

materials after a 7 hr soak. In a more severe test, with the boots completely filled with water and saturated, as would occur, for example, in a large stream crossing, the synthetic materials may be more efficacious than more traditional insulated leather boots. Under similar environmental conditions, completely waterproof boots would simply trap moisture inside the boot. The rapid recovery of synthetic-leather boot regional insulation to nearly pre-soak levels is an important characteristic which must be considered if exposure to surface moisture is not a chronic problem. The effect of surface moisture on the cold weather protection afforded by different footwear varies with the nature of the exposure to moisture and the construction and materials of individual boots.

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FIGURE LEGENDS

Figure 1. Location of thermally isolated regions of the copper foot model.

Figure 2. Standardized soak and recovery values (observed minus initial dry insulation divided by initial dry insulation) plotted against time for an insulated leather cold-weather boot.

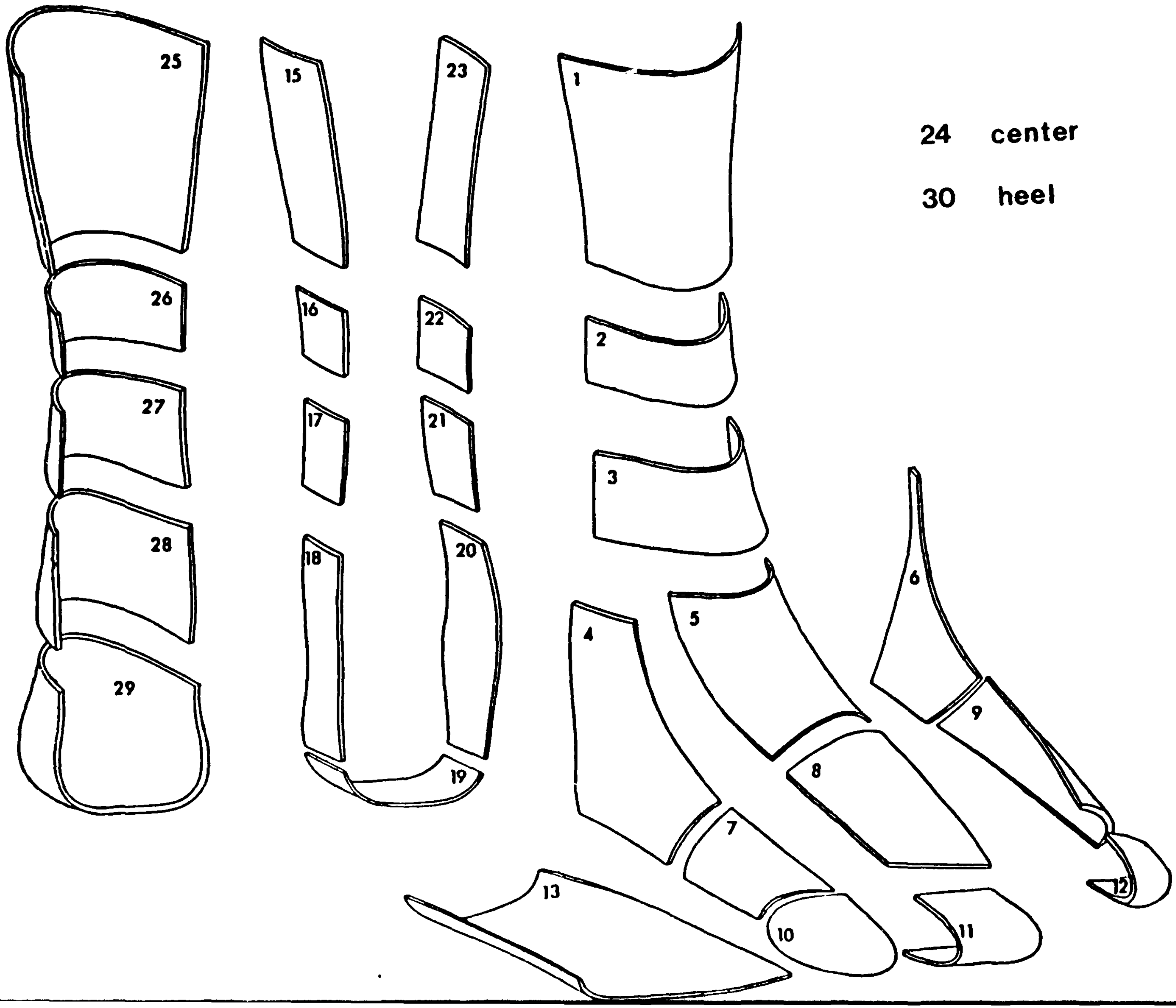
Figure 3. Standardized soak and recovery values plotted against time for an insulated leather-synthetic boot.

Table 1. Insulation values for 7 boots dry, soaking in 5 cm water, and recovering after removal from water.

Test Results

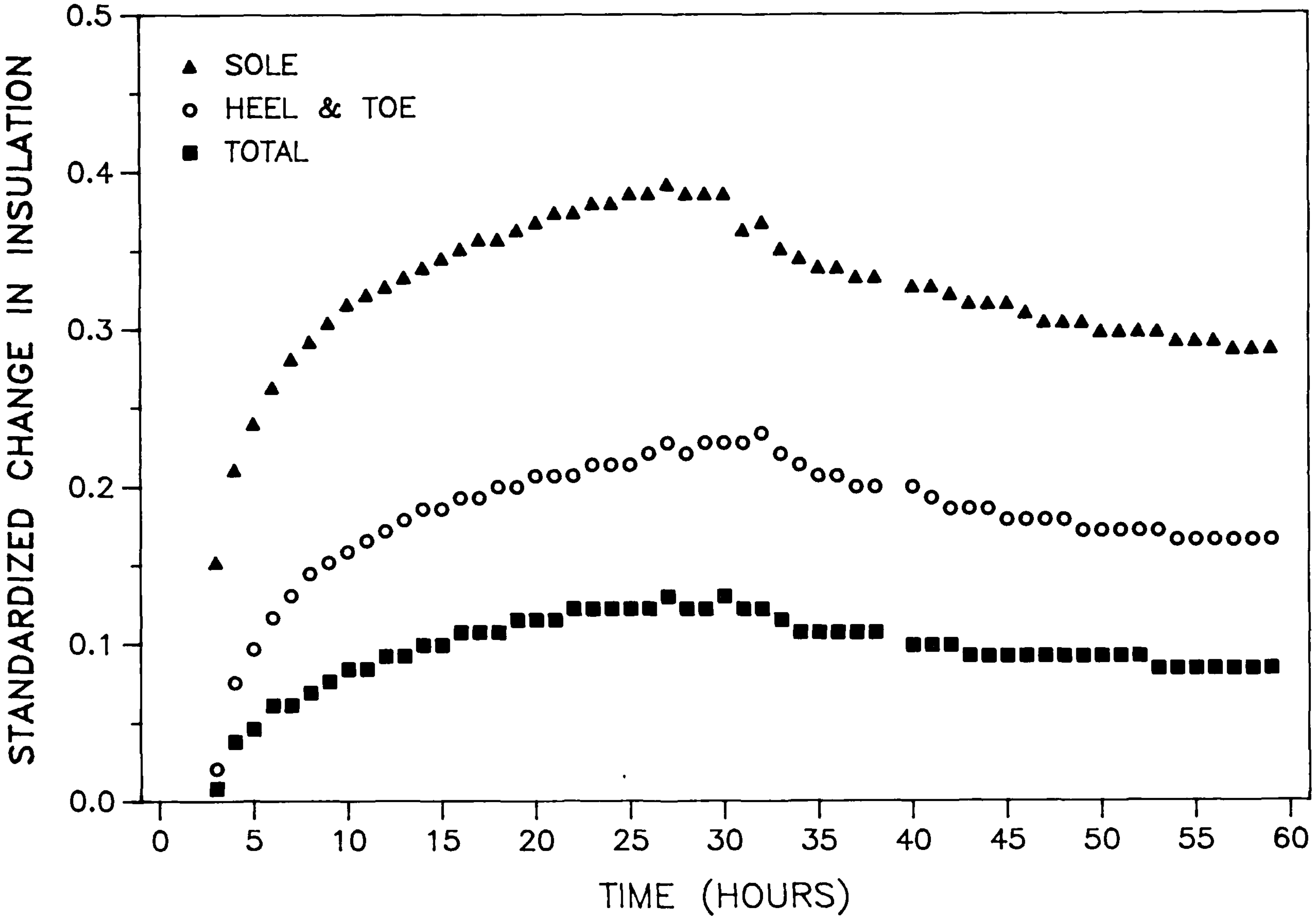
Boot Type	Region	Dry Insulation ($m^2 \cdot K/W$)	Insulation after 7 hour soak ($m^2 \cdot K/W$)	percent decrease	Insulation after 7 hour recovery ($m^2 \cdot K/W$)	percent recovery
insulated leather synthetic boot	total	0.209	0.191	9	0.185 a	88
	sole	0.259	0.206	20	0.216	83
	heel & toe	0.205	0.167	18	0.163	80
hiking boot with PTFE	total	0.188	0.172 b	8	0.177	94
	sole	0.268	0.209	22	0.233	87
	heel & toe	0.200	0.160	20	0.176	88
hiking boot (2 runs)	total	0.197	0.164	17	0.171	87
	sole	0.254	0.180	29	0.212	84
	heel & toe	0.197	0.140	29	0.164	84
leather combat boot (2 runs)	total	0.192	0.180	7	0.186	97
	sole	0.260	0.202	23	0.242	93
	heel & toe	0.186	0.160	14	0.181	98
leather cold weather boot	total	0.203	0.191	6	0.181 c	89
	sole	0.265	0.194	27	0.177	67
	heel & toe	0.225	0.197	12	0.180	80
all leather mountain boot	total	0.163	0.126	23		
	sole	0.310	0.140	55	—	—
	heel & toe	0.200	0.164	18		
shoe pac with felt liner	total	0.312	0.309	1	0.312	100
	sole	0.338	0.327	3	0.338	100
	heel & toe	0.310	0.302	3	0.312	101

a. extended soak (23 hour total)
b. 5 hour soak
c. extended soak (31 hour total)
d. dry values unstable in repeated runs



24 center

30 heel


SOLE
HEEL & TOE
TOTAL
STANDARDIZED CHANGE IN INSULATION
0.0
0.1
0.2
0.3
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5
10
15
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25
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45
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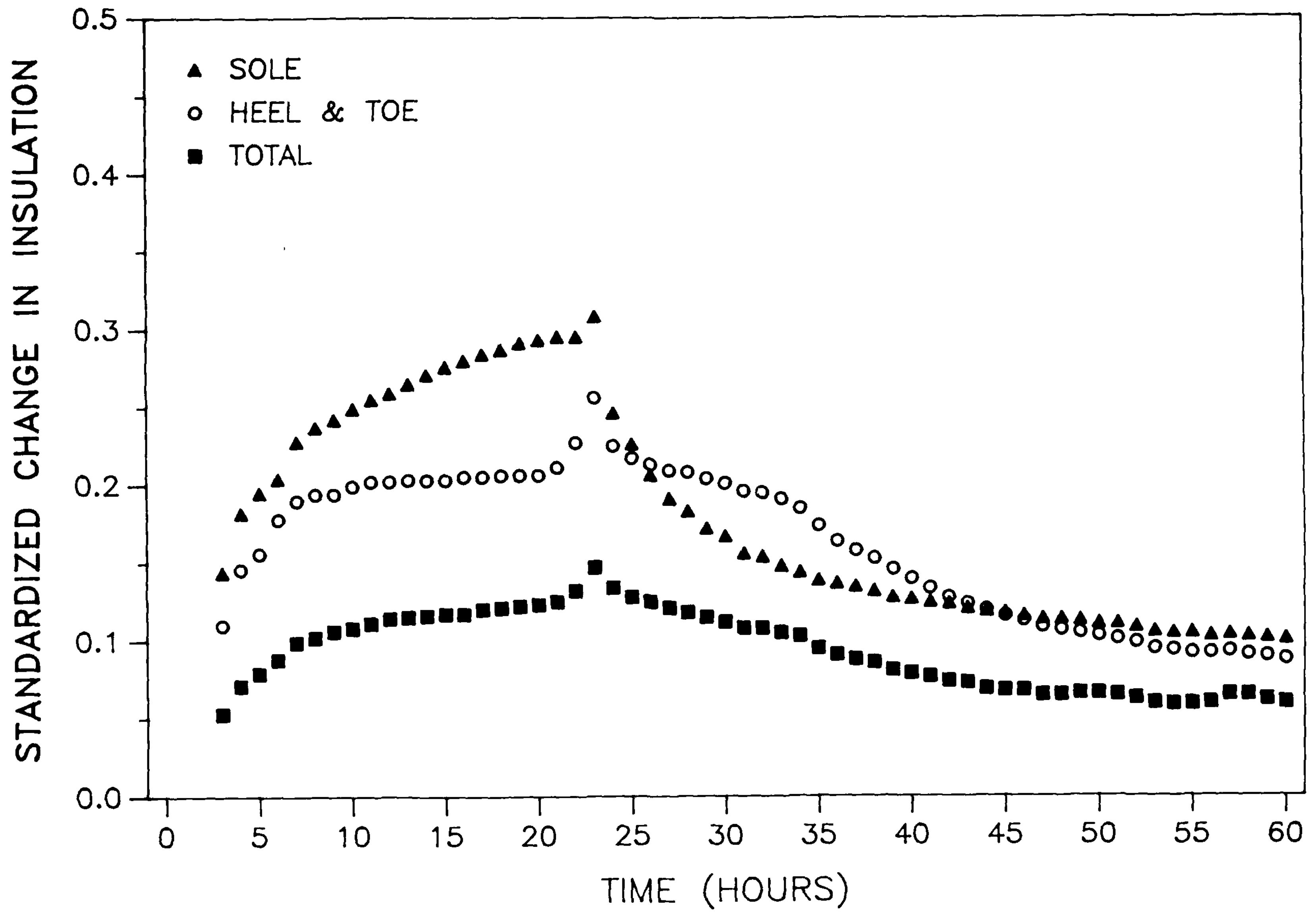
TIME (HOURS)



SOLE
HEEL & TOE
TOTAL
STANDARDIZED CHANGE IN INSULATION
0.0
0.1
0.2
0.3
0.4
0.5
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10
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20
25
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TIME (HOURS)

END

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